Hadro-Production Experiments: Impact on T2K and LBNE

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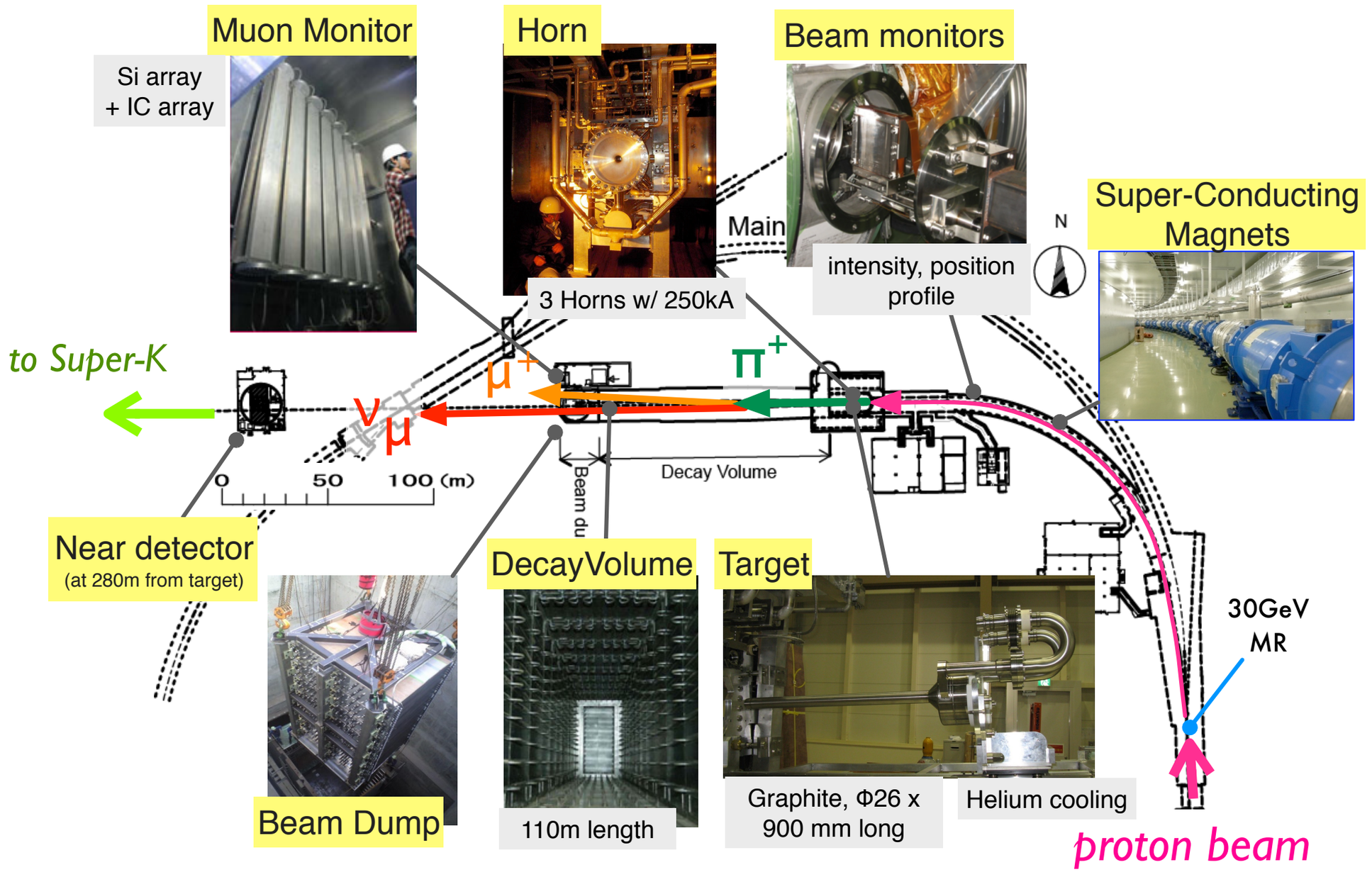
Outline

- T2K
  - Datasets used
  - Flux prediction
  - Flux uncertainties
- LBNE
  - Currently Available Data
  - Potential future measurements

T2K Beam



- 31 GeV/c protons on 91.4 cm long graphite target (ρ=1.8 g/cc, 1.9 λ), fixed in place

T2K Beam Flux

- ND and SK are both ~2.5° off-axis
- Very different detector technologies so many cross section and detector uncertainties don't cancel

- Much of this talk will follow "T2K Neutrino Flux Prediction", Phys Rev D, **87** 012001 (2013)
- Fluka 2008 was used at time of paper for hadron interactions in target + baffle
- Most important hadroproduction data sets for T2K are Allaby, Eichten, and NA61 (see next few slides)

Allaby Data

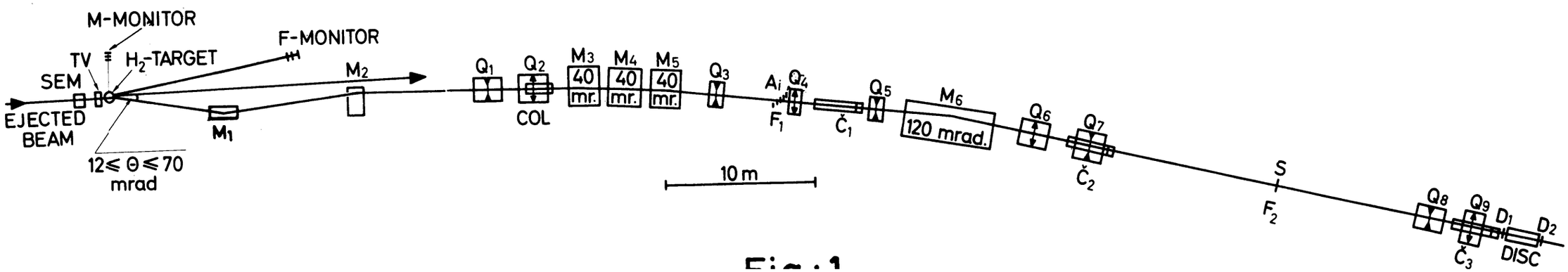
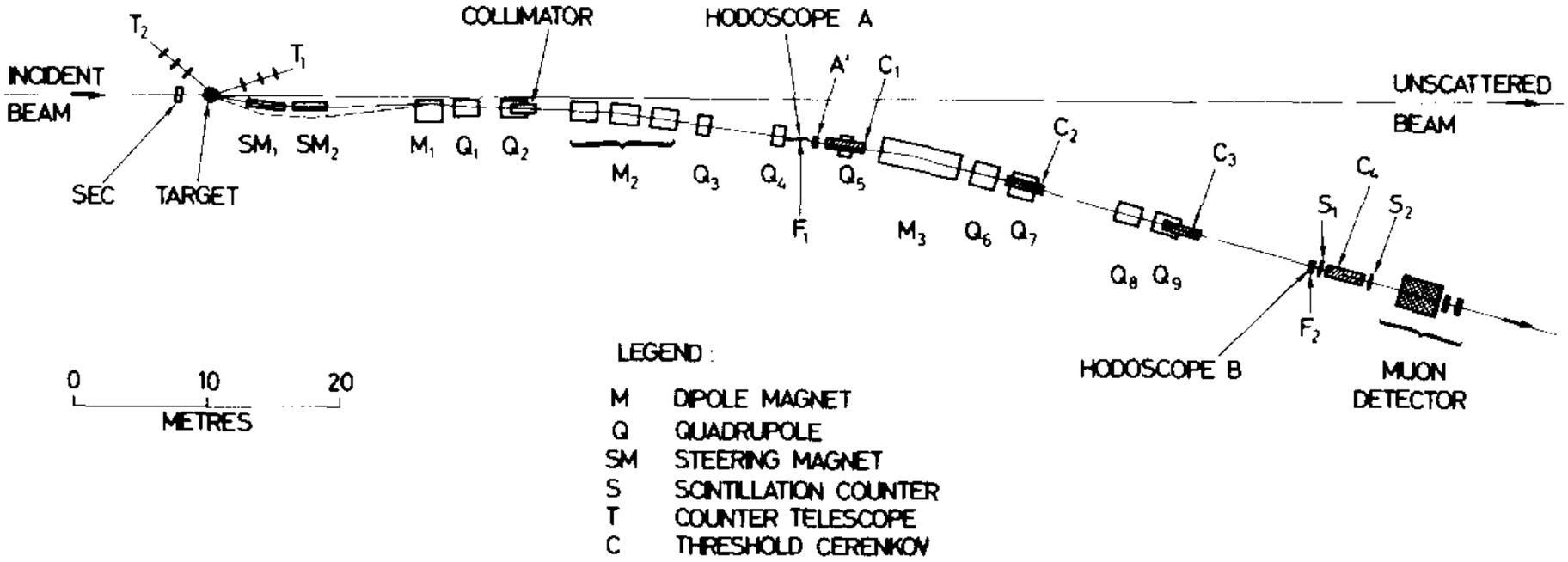


Fig. 1

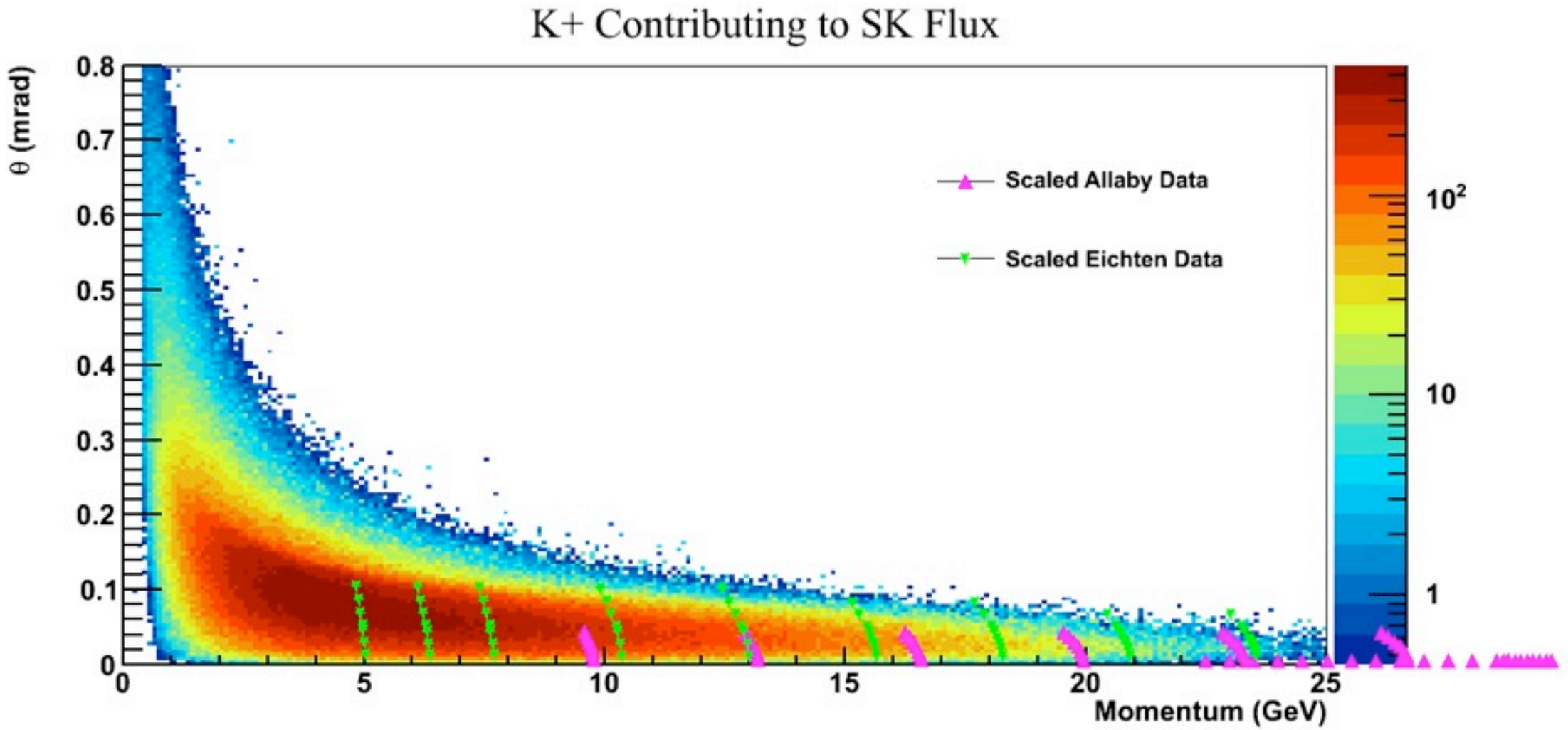
- Data release as J. V. Allaby et al., Tech. Rep. 70-12 (CERN, 1970).
- Took data with a 19.2 GeV/c beam on p,Be, Al, Cu, and Pb targets
- Measured p,pbar, K+-, π+- production from 12.5 to 70 mrad and p from 4.5 to 14 GeV/c

Eichten Data



- Published in T. Eichten et al., Nucl. Phys. B 44, 333 (1972).
- Took data with a 24 GeV/c beam on Be, Al, Cu, and Pb targets
- Measured p,pbar, K+-, π+- production from 17 to 127 mrad and p from 4 to 18 GeV/c

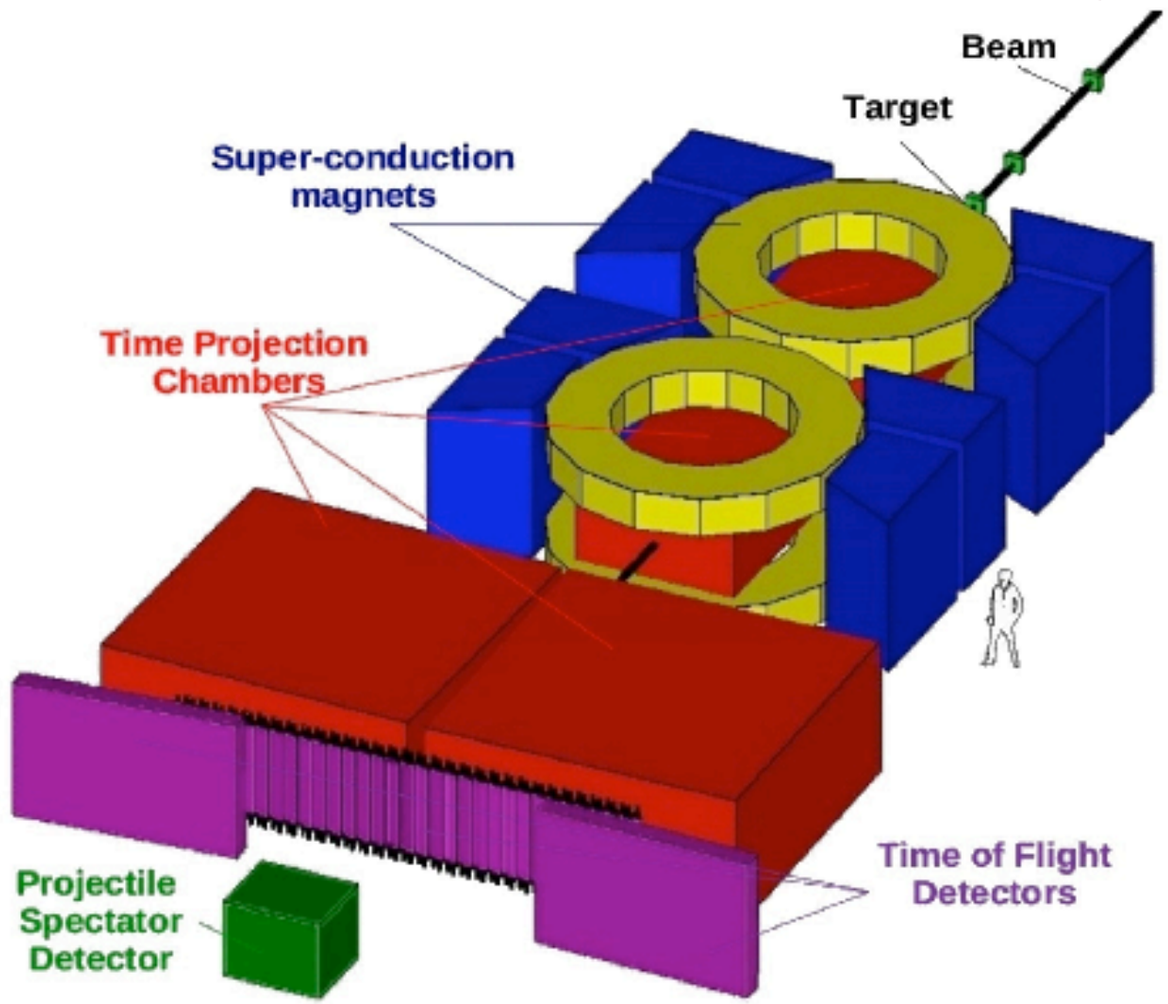
Eichten and Allaby K^+ coverage



- Plot from Scott Johnson, scaled by x_f and p_t

SPS Heavy Ion & Neutrino Experiment

- 2 TPCs inside superconducting magnets
- 2 TPCs after magnets
- ToF detectors
- A new projectile spectator detector is being commissioned
- Had used a variety of targets and beams

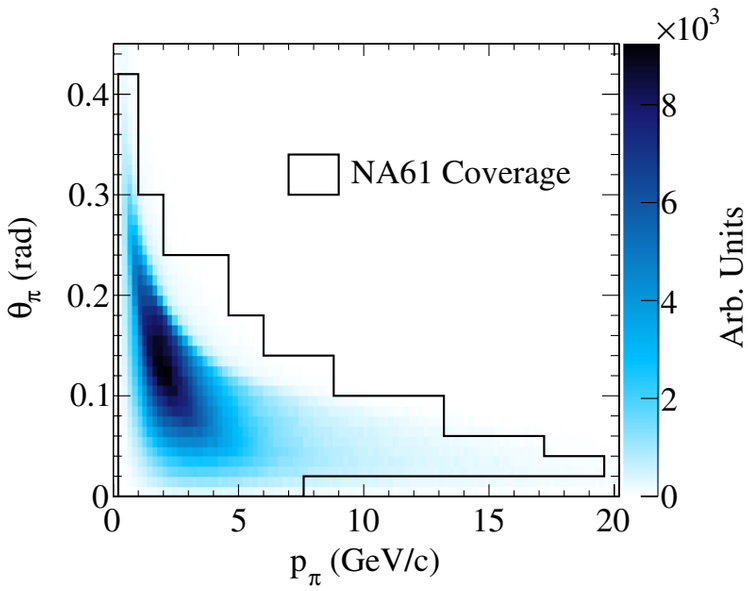


NA61 Data for T2K

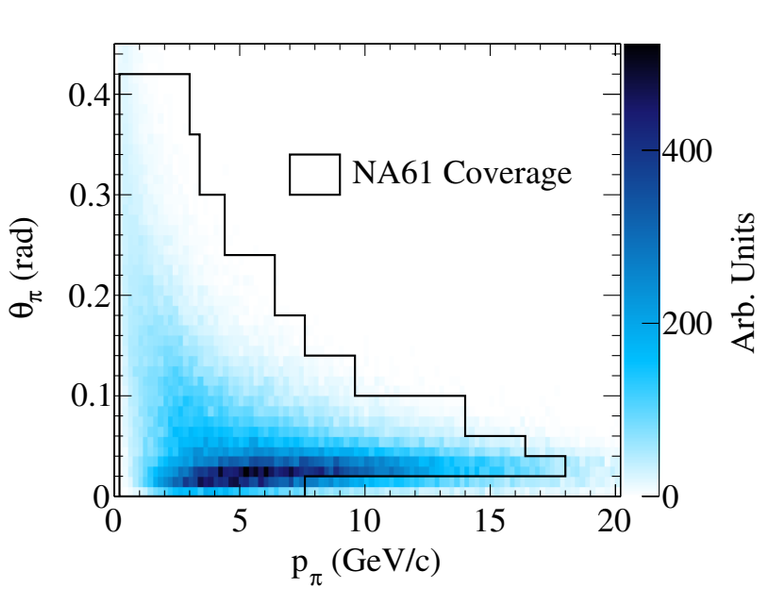
Data	Year	evts (x10^6)	Status
2 cm target	2007	0.7	$\pi^{\pm}$:Phys. Rev. C84 (2011) 034604 K^{+}:Phys. Rev. C85 (2012) 035210 Λ: Phys. Rev. C89 (2014) 025205
2 cm target	2009	5.4	Preliminary $\pi^{\pm}$, $K^{\pm}$, p, K^0_s, Λ To be published soon
full target	2007	0.2	$\pi^{\pm}$ method: Nucl. Inst. Meth. A701 (2013) 99
full target	2009	2.8	End of 2014?
full target	2010	10	

- All data taken with protons at 31 GeV/c

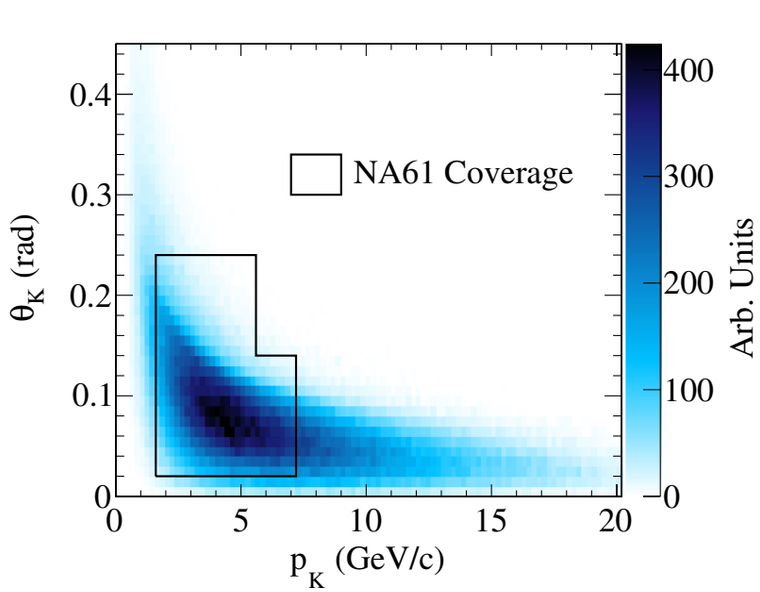
NA61 Coverage for T2K



(a) π^+



(b) π^-



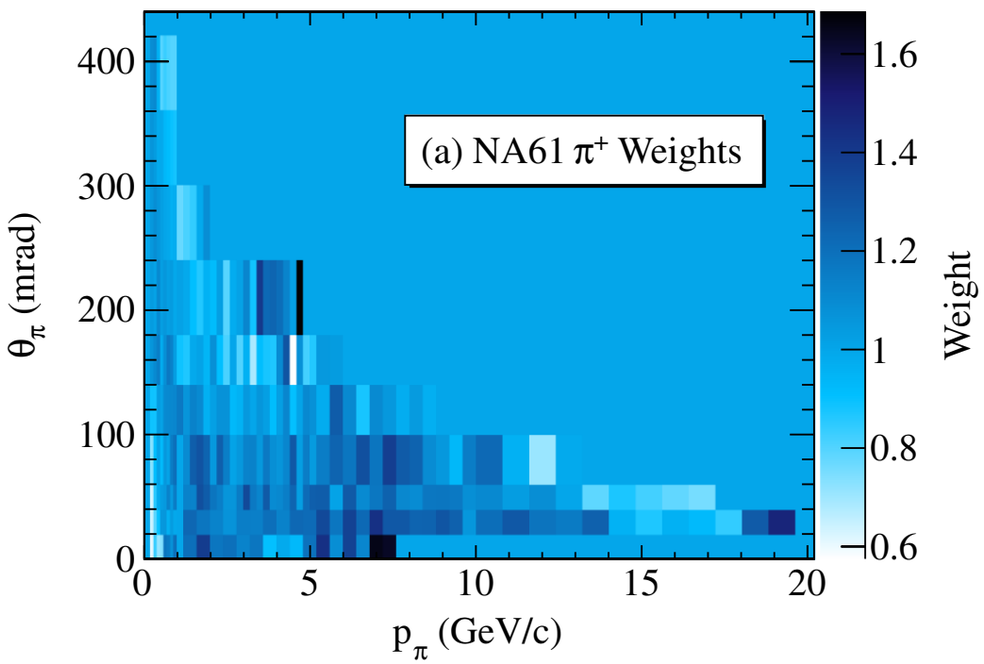
(c) K^+

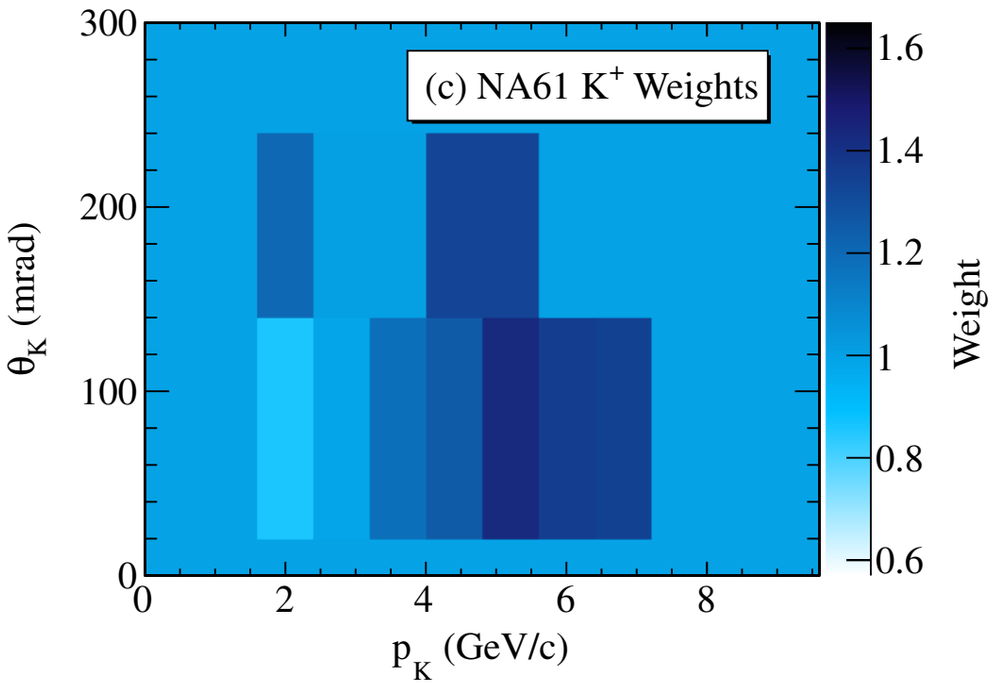
- Colors indicate contribution to T2K flux at SK
- Covers 90% of π and 60% of K^+ phase space
- Will increase in future NA61 analyses (later this year)

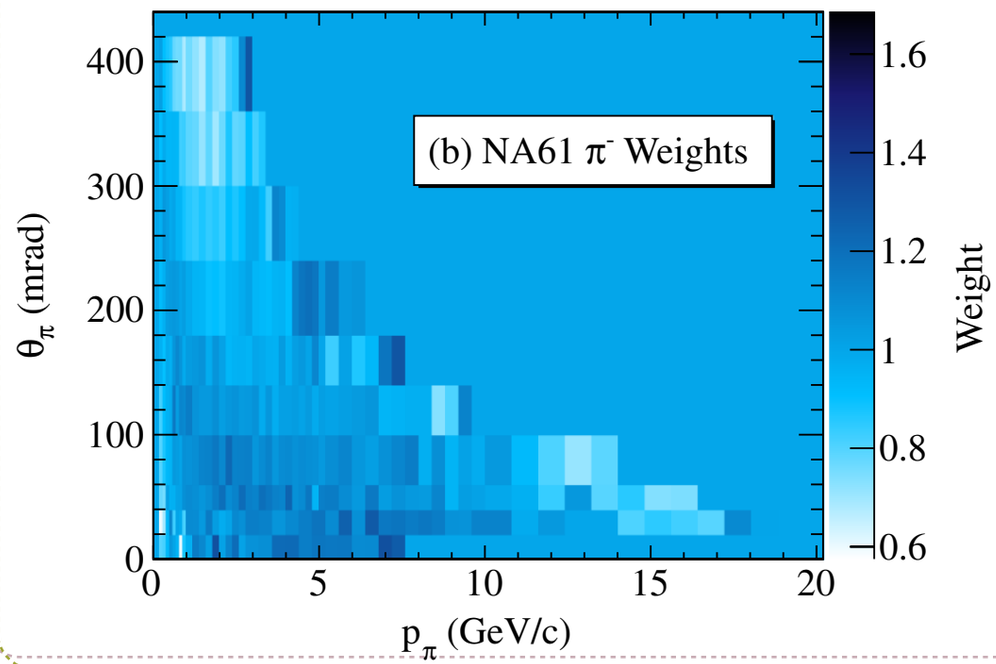
Reweighting

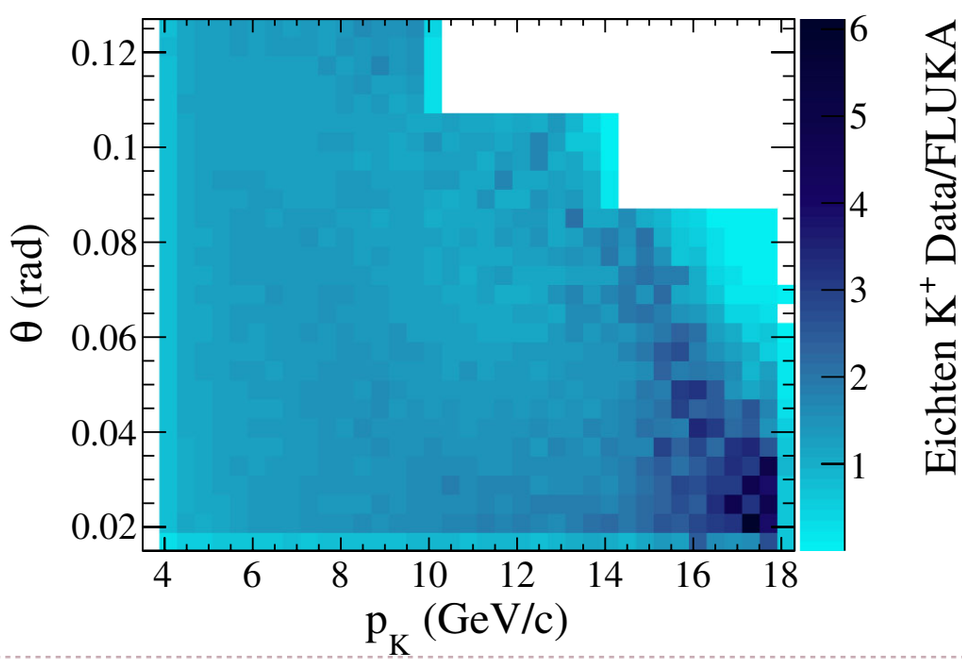
- Weights obtained from comparisons of measured differential multiplicities to MC predictions
- Reweighting also done for overall σ_{prod}
- Eichten and Allaby Be data are scaled by x_f and target material to cover K regions not covered by NA61
  - Material scaling uses parameterization suggested in Bonesini et al, Eur. Phys. J. C 20, 13 (2001).
- Rescaled NA61 data also used for tertiary interactions (including in Al)

Weights to Fluka



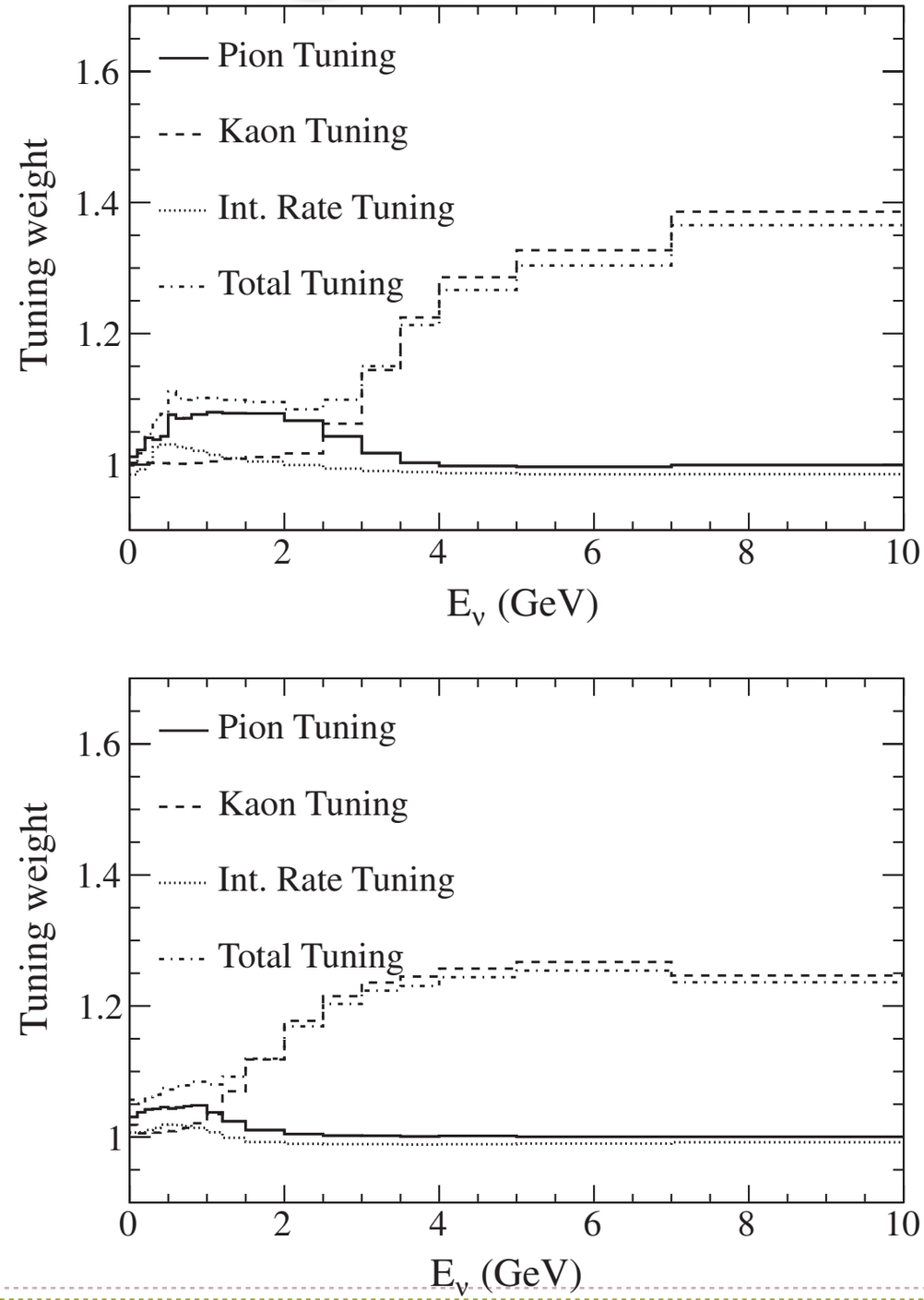






Flux Weights

- Compared to Fluka 2008
- Top plot shows ν_μ flux weights
- Bottom plot shows ν_e flux weights



Pion Uncertainties

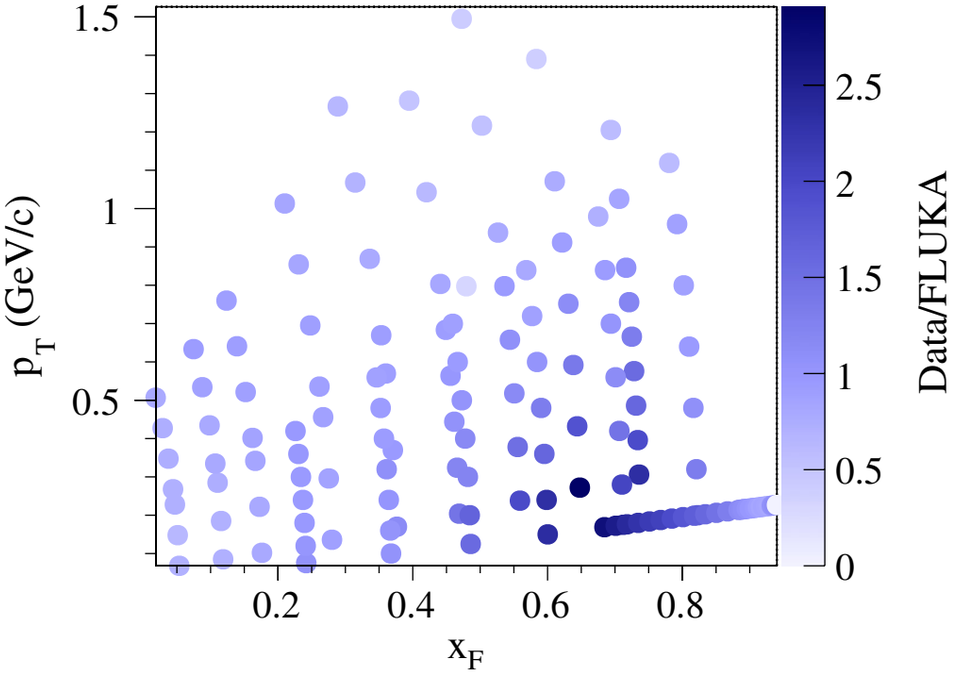
- Uncertainties from NA61 measurements are used
  - Parameters varied according to covariances
- There are also additional errors due to rescaling for different p. These are evaluated by comparing to BNL E-910 data (protons on Be at 12.3 and 17.5 GeV/c)
- For region outside of NA61, error comes from comparison to a BMPT fit of NA61

Kaon Uncertainties

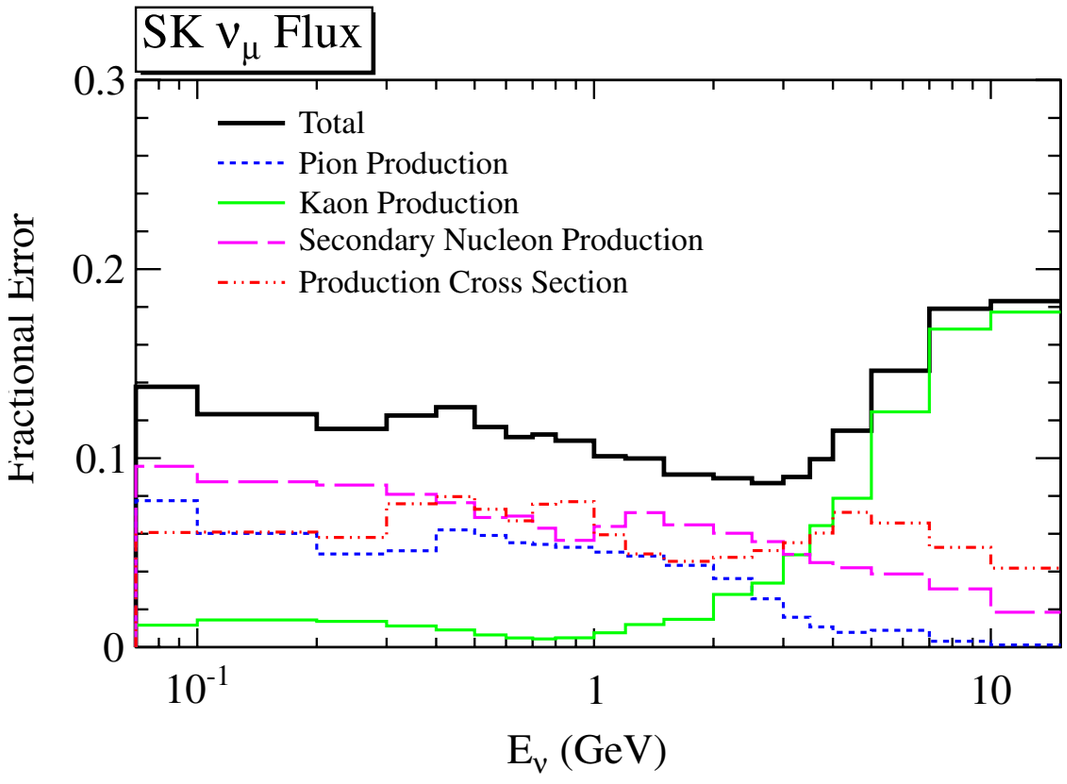
- Again uncertainties on data values are used, taking in to account correlations
- Looking at the Al data from Eichten and Allaby gives an uncertainty due to target material scaling
- Uncertainty on momentum scaling comes from scaling Allaby data to Eichten incident momentum
- Again a comparison to a BMPT fit is use to evaluate errors outside of data coverage.

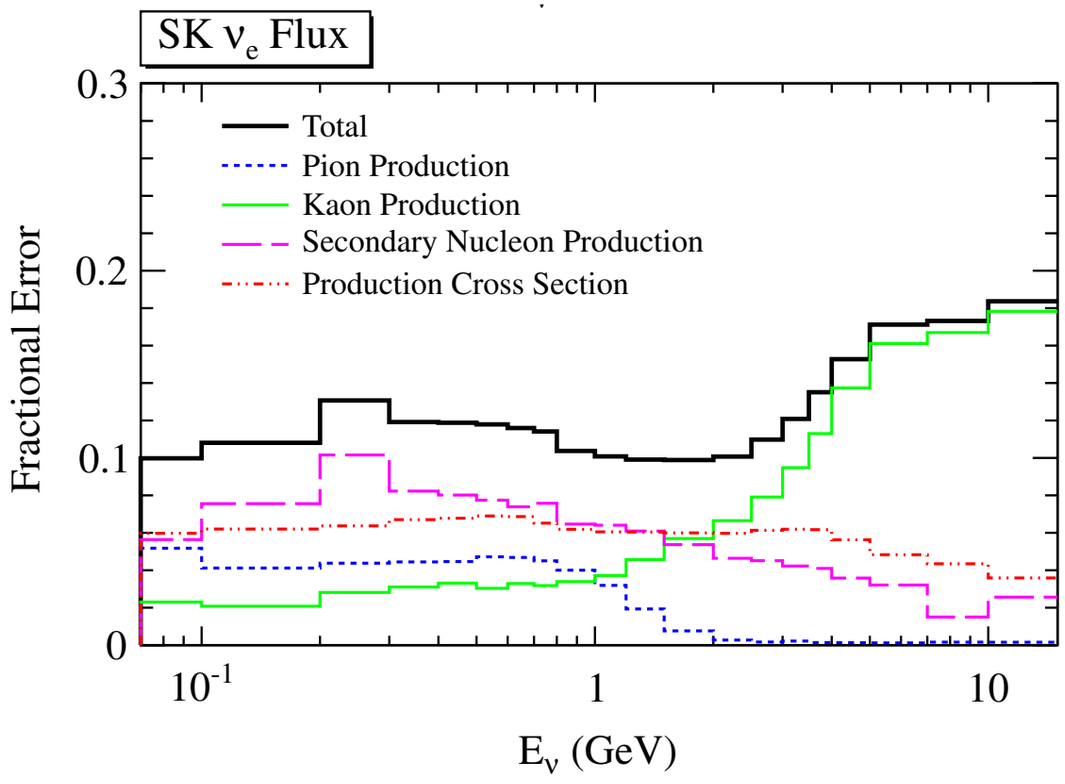
p,n Uncertainties

- secondary p,n make up 16%, 5% of flux
- Comparisons between FLUKA and Eichten/ Allaby proton data used for x_f <0.9. Discrepancy is the uncertainty.
- Above x_f >0.9, a 100% uncertainty is used



Hadron Production Uncertainties



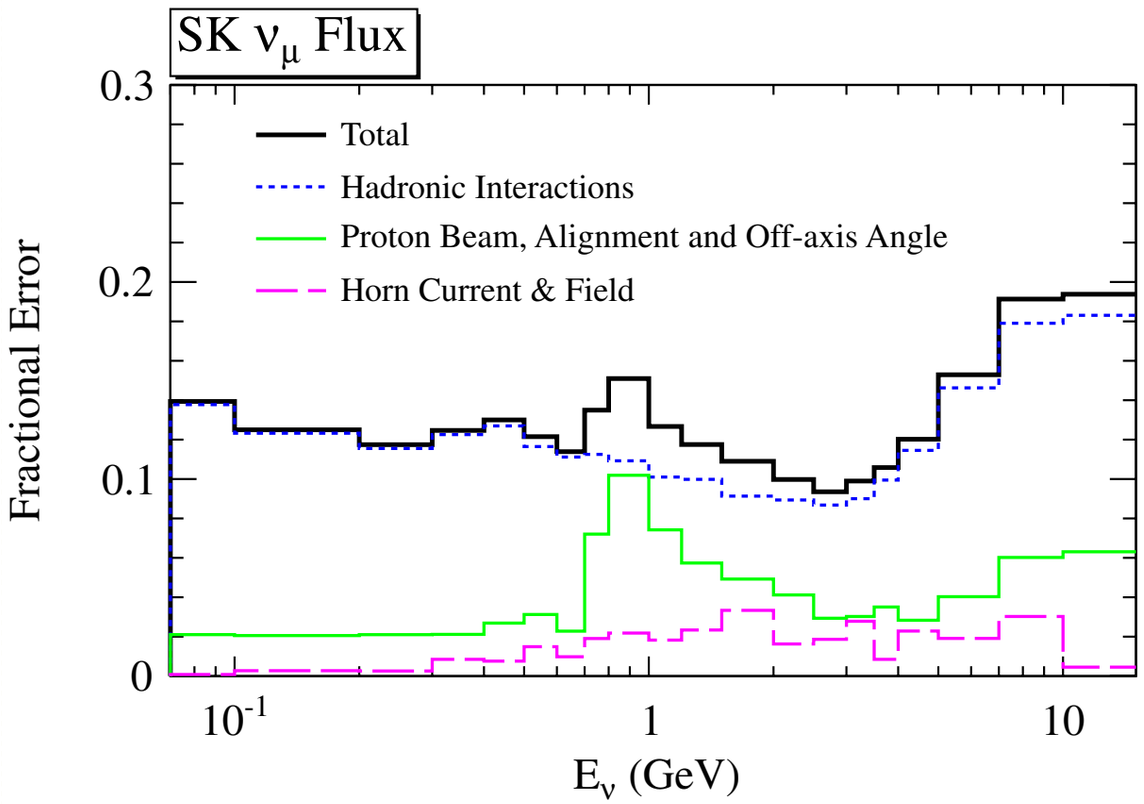


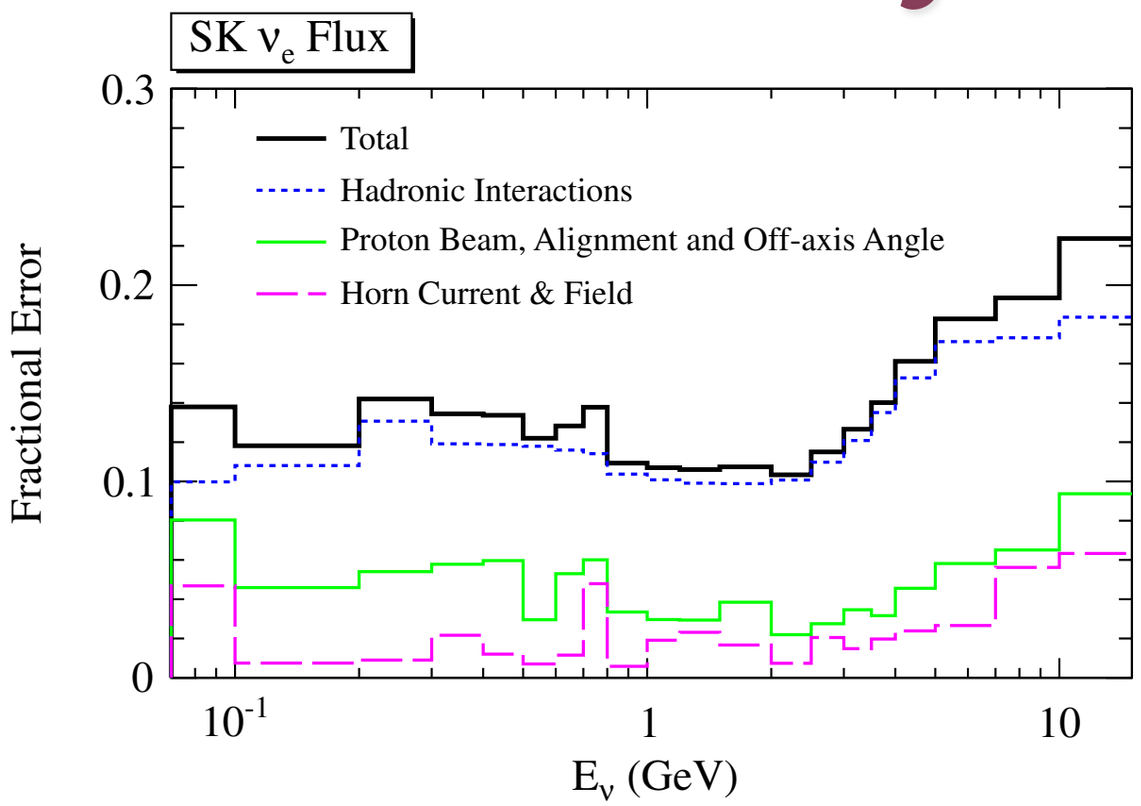
- π and K uncertainties are 6% or less below 3 GeV
- Largely dominated by nucleon uncertainties

Other Sources of Flux Uncertainty

- Other beam effects were largely handled by tweaking beam MC and reweighting
  - Beam size, position, and angle
  - Off-axis angle
  - Target and horn alignment
  - Horn current and B-field

Total Flux Uncertainty



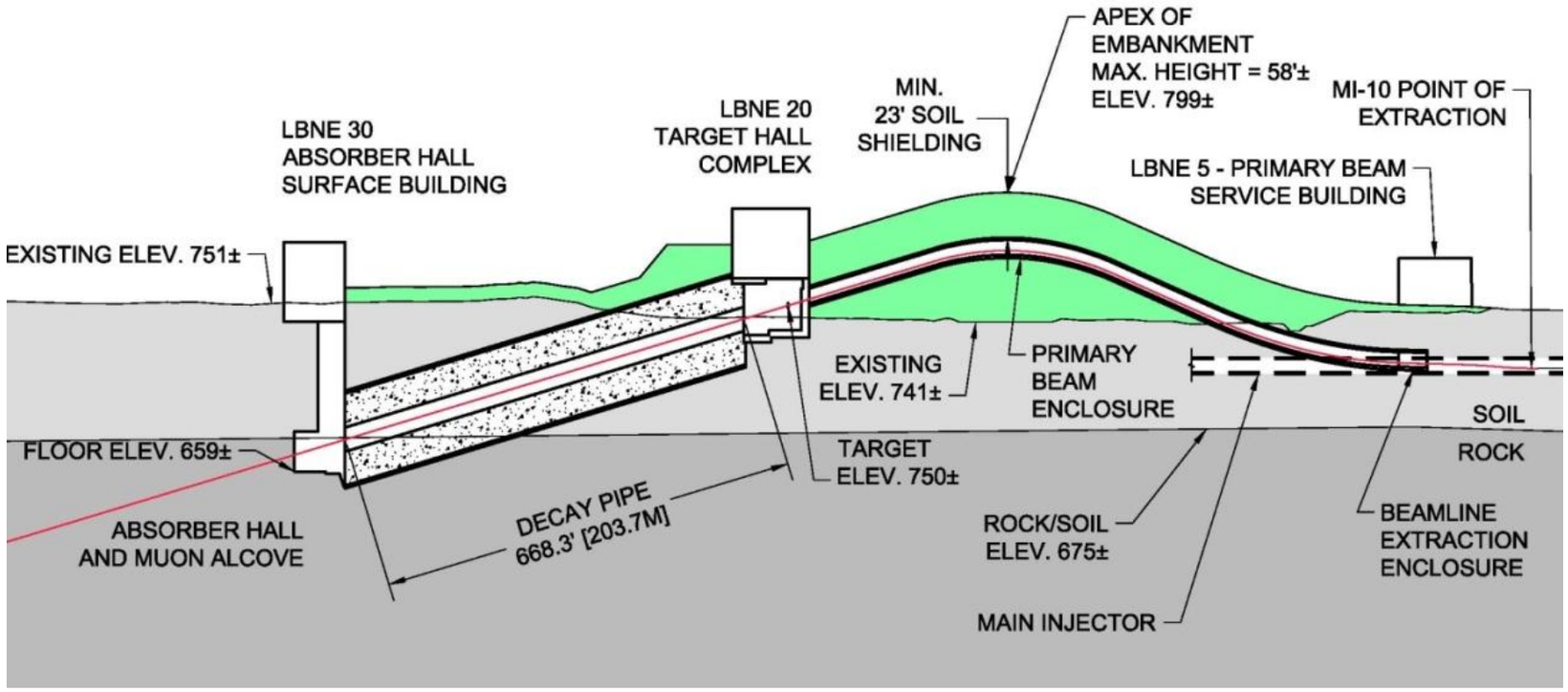


- Dominated by hadron production
- Still more improvements to come, but currently the flux uncertainties are ~10-12% in the oscillation range of interest

Prospects for Improving T2K Uncertainties

- 2009 Thin target data
  - >5x more statistics
  - Data will cover more phase space (especially for K)
  - Will have p, Λ, and K^0 data
- 2009 Long Target data

LBNE Beam

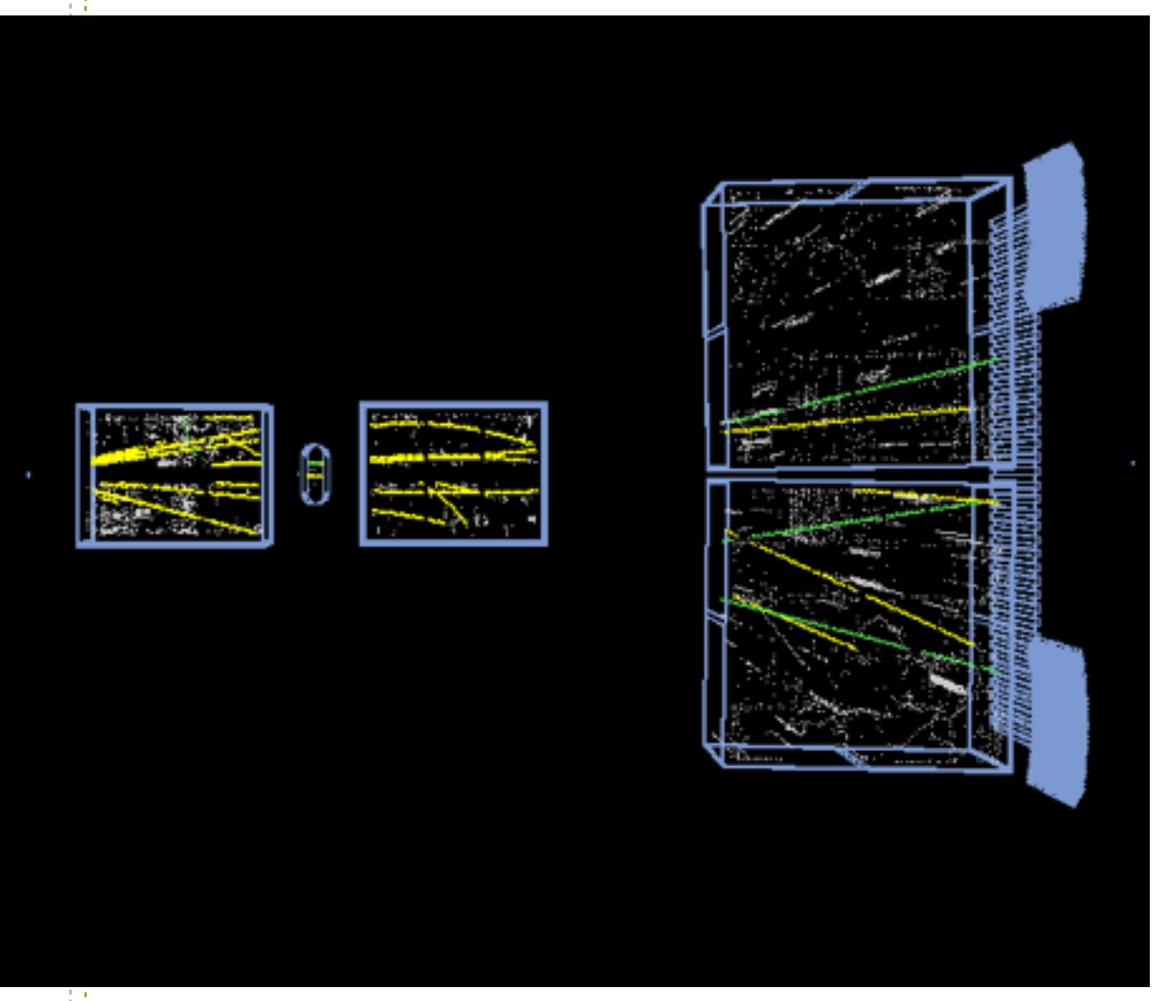


- 80-120 GeV/c protons
- 1.2 MW option currently has a graphite target, will likely be fixed in place
- Near and Far detectors likely will have very different detector technologies

Datasets for LBNE

- MIPP: 120 GeV/c protons on a think and thin target. Preliminary NuMI thick target data presented in April 2014 (<10% errors in most bins)
- NA49: p+C data at 158 GeV/c
- Barton et al: data at 100 GeV/c, but disagrees with NA49 by 20% in region of overlap

NA61 and LBNE

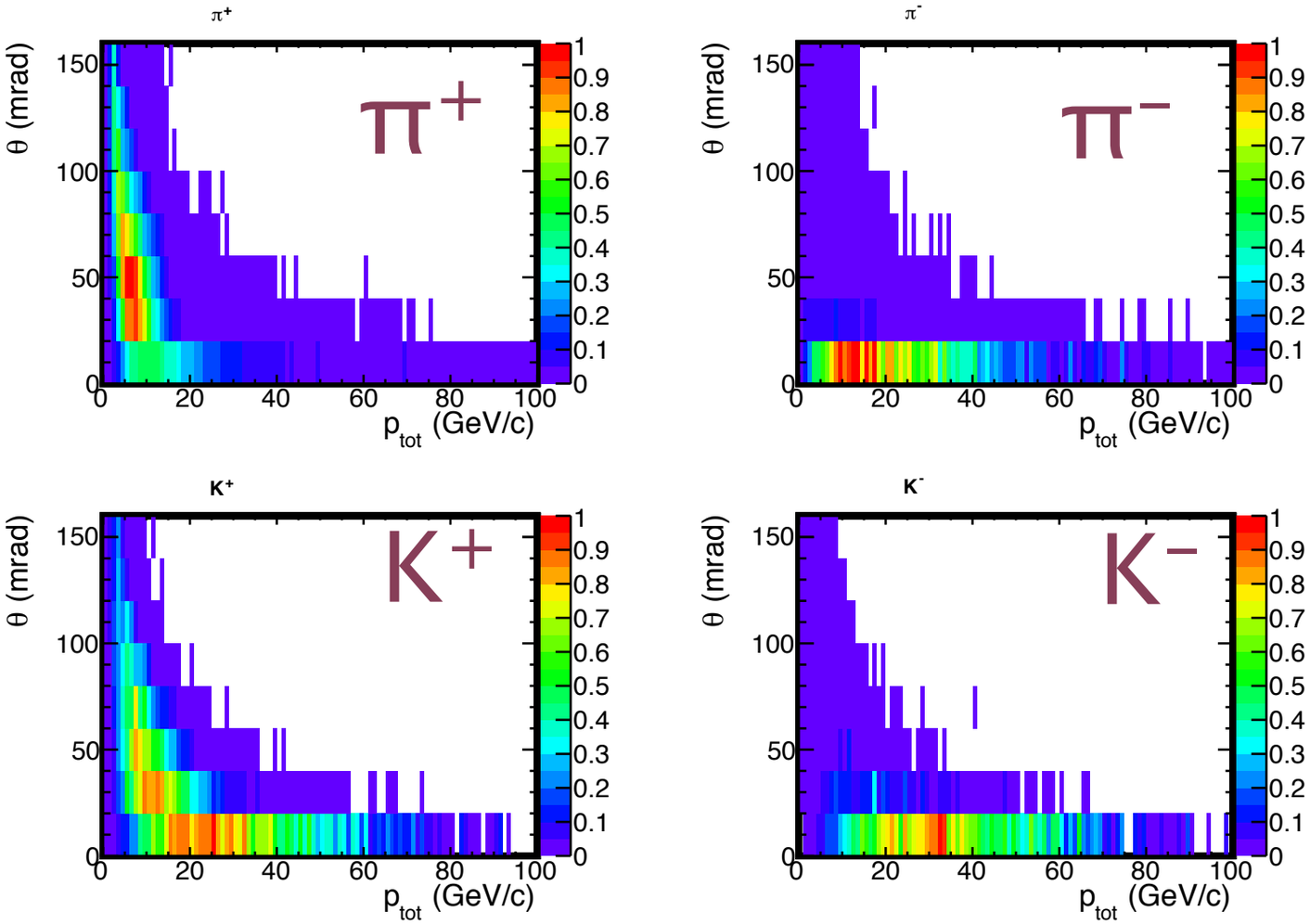


120 GeV p+C event in NA61

- Proposal being submitted to DOE to take data with higher energy protons in NA61 that would benefit Fermilab experiments
  - proton (and pion) data at 120 GeV/c on thin Be, C, and Al targets
  - proton (and pion) data at ~60 GeV/c on thin targets

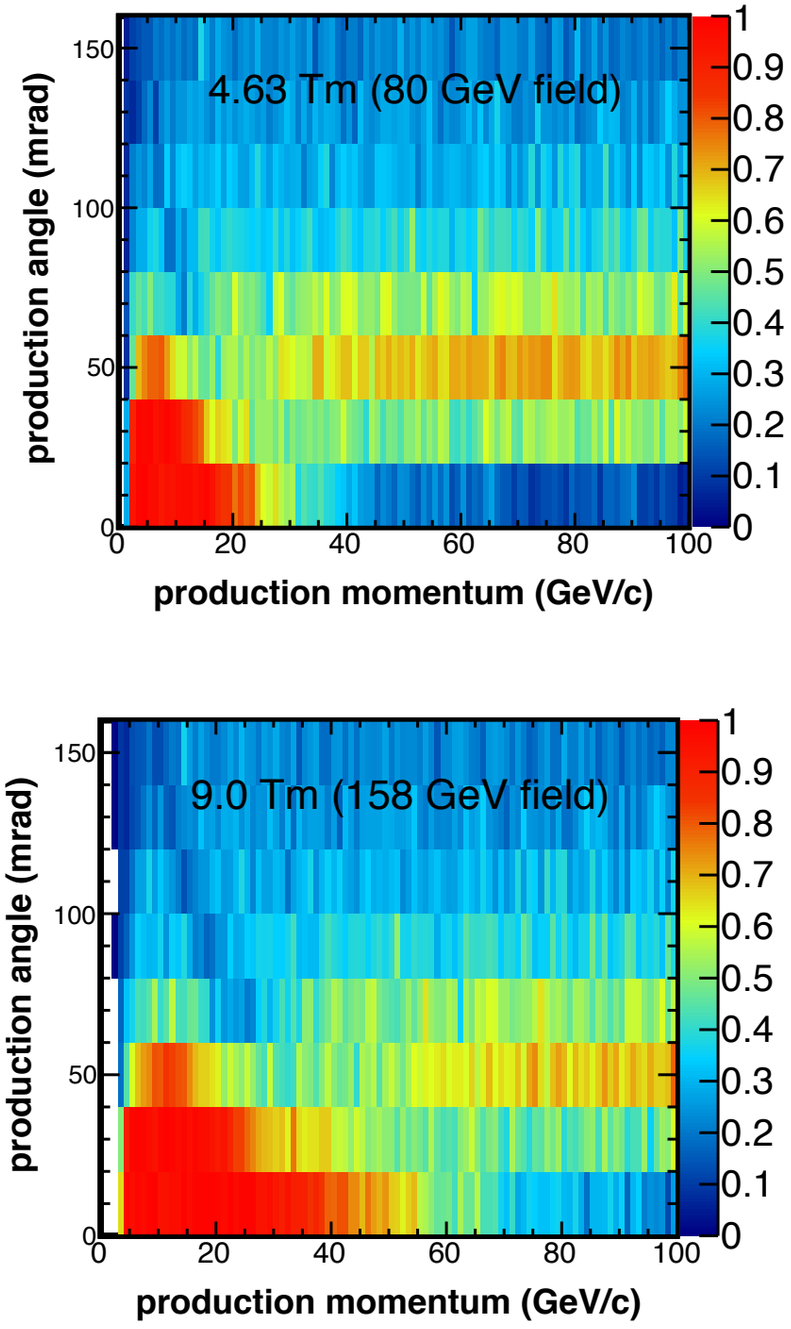
LBNE Phase Space

π and K contributions to flux at LBNE far site

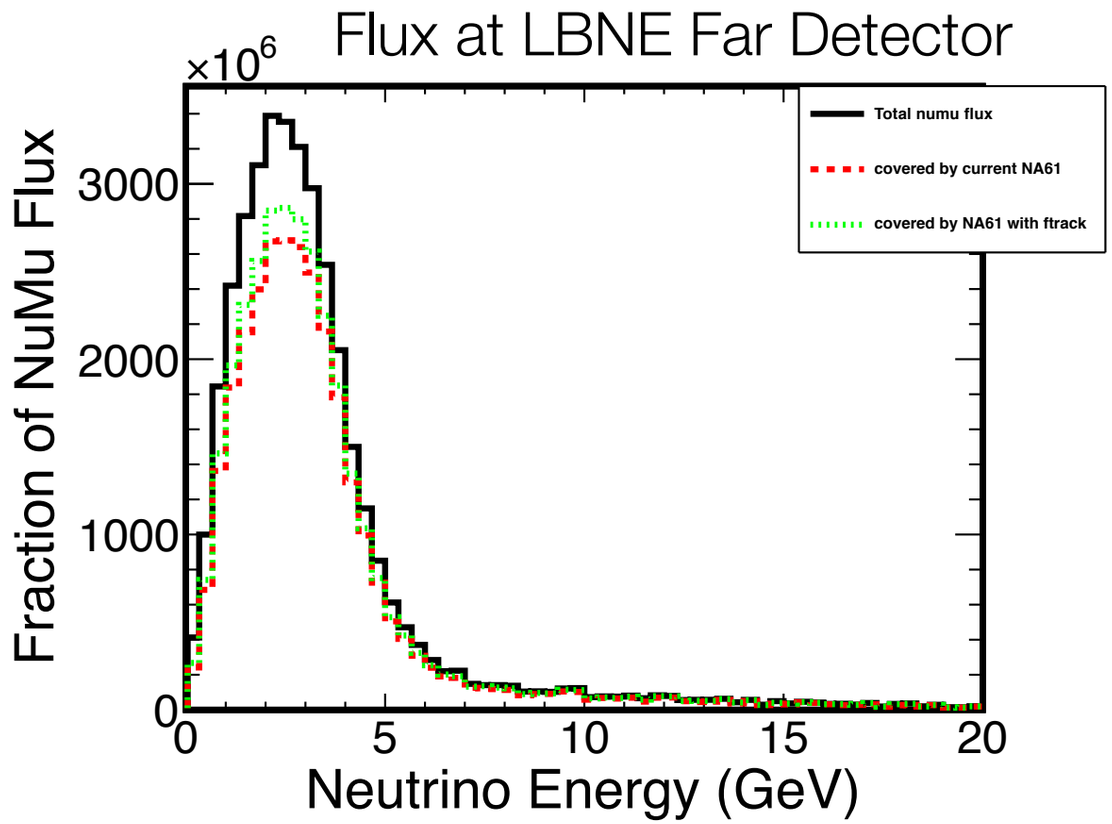


- Regions of phase space that contribute to LBNE flux are well matched to NA61 phase space

NA61 Acceptance



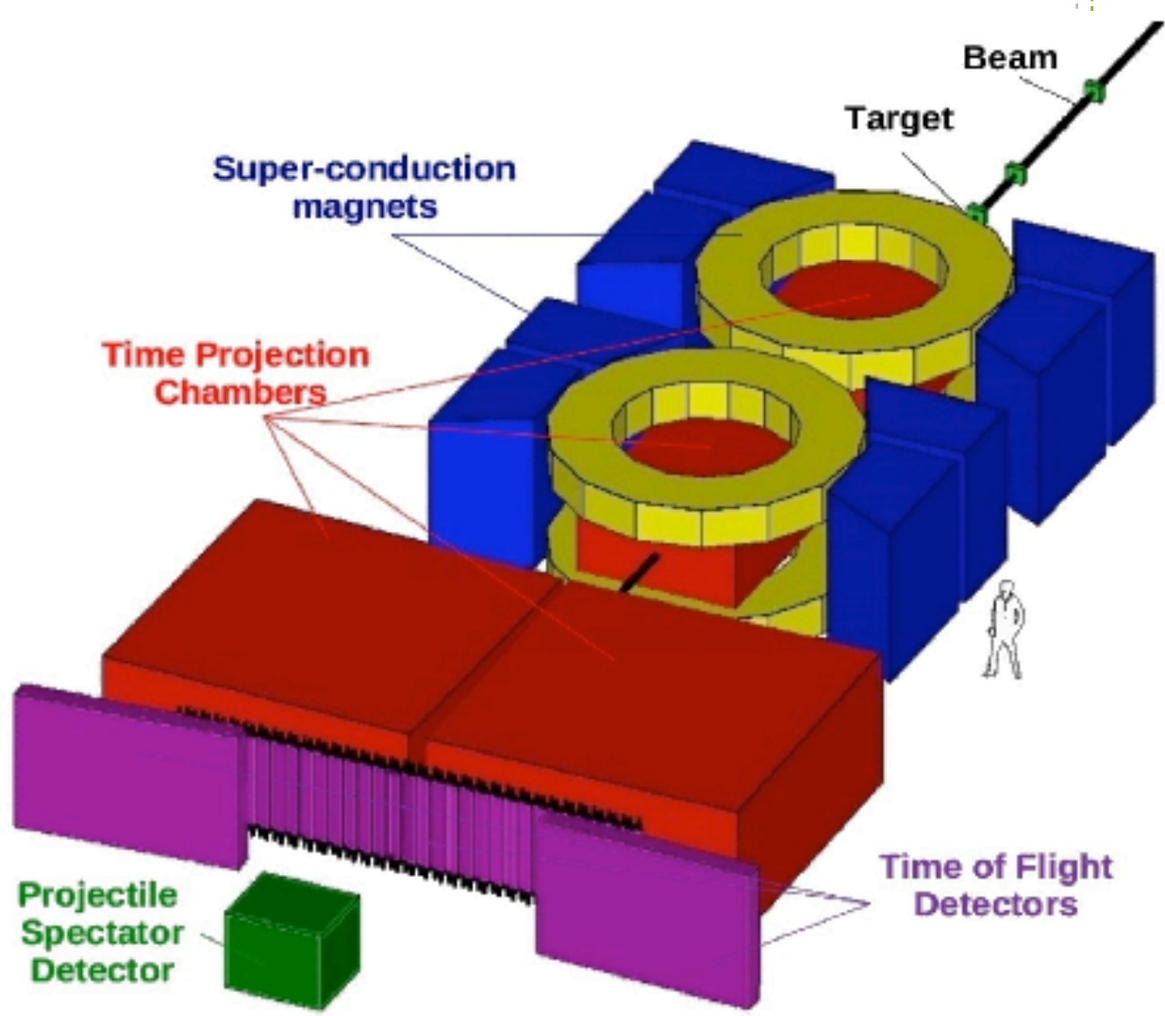
LBNE Coverage



- Current NA61 has good coverage of charged π,K that contribute to LBNE flux (red line).
- With additional forward tracking could be improved (green line).
- (The remainder is from n, K^0, and Λ^0. Some of this should be possible to measure too.)

Neutron Measurements?

- A new projectile spectator detector (an HCAL) was commissioned for NA61 in 2013
- Could potentially use this to make direct measurements of forward n production



Summary

- T2K has benefited greatly from a suite of thin and thick target measurements from NA61
- Increased statistics and data analysis improvements from NA61 will improve this over the next 2 years
- Thin target data at 60-120 GeV/c could similarly benefit LBNE. Possible opportunity to start to take this data at NA61 in 2015